The optical counterpart to γ-ray burst GRB970228 observed using the Hubble Space Telescope

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Although more than 2,000 astronomical gamma-ray bursts (GRBs) have been detected, and numerous models proposed to explain their occurrence[1], they have remained enigmatic owing to the lack of an obvious counterpart at other wavelengths[2–5]. The recent ground-based detection[6,7] of a transient source in the vicinity of GRB 970228[8–11] may therefore have provided a breakthrough. The optical counterpart appears to be embedded in an extended source which, if a galaxy as has been suggested[7,12], would lend weight to those models that place GRBs at cosmological distances. Here we report the observations using the Hubble Space Telescope of the transient counterpart and extended source 26 and 39 days after the initial γ-ray outburst. We find that the counterpart has faded since the initial detection (and continues to fade), but the extended source exhibits no significant change in brightness between the two dates of observations reported here. The size and apparent constancy between the two epochs of HST observations imply that it is extragalactic, but its faintness makes a definitive statement about its nature difficult. Nevertheless, the decay profile of the transient source is consistent with a popular impulsive-fireball model[13], which assumes a merger between two neutron stars in a distant galaxy.

The optical counterpart to GRB 970228 was observed with the HST Wide Field and Planetary Camera (WFPC2), on March 26[14] and April 7[15], about 26 and 39 days after the outburst, respectively. The optical counterpart was placed at the centre of the Planetary Camera (PC) field of view, so as to attain maximum spatial resolution. Three other candidates (one radio[16] and two optical[17–22]) proposed earlier as counterparts of GRB 970228 are also within the WFPC2 field of view. Observations were taken in the F606W (wide V) and F814W (I) filters[23]. Four exposures with a total integration time of 4700 seconds were taken in the F606W filter and two exposures with a total integration time of 2400 seconds were taken in the F814W filter, during each observing run. The images were corrected for bias and flat-field variations through the standard Space Telescope processing software. The number of images was sufficiently large to allow for a proper cosmic ray rejection from the flat- fielded images. The images were combined after cosmic ray rejection. Fig. 1a shows a part of the combined F606W and F814W images (for the two observations) where the optical counterpart of

the GRB can be seen at the centre. The optical counterpart is embedded in an extended source which can be seen in both passbands. An examination of the PSF of different sources also clearly shows the extended nature of this source. As seen in Fig. 1a, the angular extent of the extended source is ~ 1 arcsecond and it is elongated in the $E-W$ direction. The point source lies about 0.3 arcseconds south of the centre of the extended source. Photometry in both wavebands was carried out for the point source using the photometric software package DAOPHOT. The derived magnitudes for the point source are given in Table 1. As noted earlier, this source was first detected in the optical wavelengths about 1 day after the outburst, when the magnitudes were $V = 21.3$ and $I = 20.6$ and the magnitudes observed 9 days after the outburst were $V > 23.6$ and $I > 22.2$. The observed decline in brightness is shown in Fig. 2 with the predictions of various models (see discussion below). The $V-I$ colour of the point source has increased by about 0.6 magnitude in 25 days, which is consistent with a cooling trend, and then remained roughly constant for the following 12 days.

We tested for a possible proper motion of the point source between the two epochs (March 26 and April 7) in the two filters. We find a potential motion, both in the V and I filters, in the NW direction of about 0.006 arcseconds. Given the errors involved (this represents a 1.5 to 2 σ result), and considering the fact that the GRB is the faintest object in the field and is embedded in a nebulosity, we conclude that no proper motion has been detected.

We would like to point out that even without discussing the probability of finding a variable star in the error box of the GRB during the given time frame, it is possible to rule out the possibility that the optical transient is actually an unrelated nova, dwarf nova, flare star, or a supernova. The evolution of the colours is inconsistent with that of novae (the transient becoming redder rather than bluer following maximum)[24], and the value of (V-I) (which is ∼0.0 for dwarf novae), and its development are inconsistent with those of dwarf novae[25] (correction for absorption indicated by the LECS (0.1 - 10 kev) observations on board the SAX satellite does not change this conclusion). The duration of the event is longer by orders of magnitude than those of stellar flares[26]. Although supernovae decay in visual wavelengths at a slower rate than observed for the optical transient, they can decay in the UV as fast as 2.5 magnitudes per day[27]. Thus, a supernova at the appropriate redshift (z ∼ 1–2), could appear to decay in the visual (UV rest frame) at

the observed rate. However, the observed fast decline in I would imply that the redshift of this supernova is > 1. Such a large redshift would make this object brighter than the brightest supernovae (observed either at low[28], or at high[29,30] redshift) by about 2 magnitudes at the peak, thus making it improbable to be a supernova.

In order to determine the magnitudes for the extended source, the point source was subtracted using a PSF derived from other point sources in the images. DAOPHOT was used to derive the magnitudes of the extended source within a radius of 0.6 arcseconds. The resultant magnitudes are given in Table 1. The angular dimensions of the extended source are consistent with earlier estimates from the ground; however, its brightness appears lower by about 0.9 magnitudes in the March 26th observation. At present it is not entirely clear whether this discrepancy represents a real decline, or whether it simply results from the inability of the ground-based observations to resolve the point and extended sources. In order to investigate this further, we performed an experiment to simulate the ground-based observations of March 9. We used the combined F606W image and artificially increased the brightness of the point source to $V = 24.0$ (as predicted by the best theoretical models, see below). We then smoothed the image to simulate 1-arcsecond seeing from the ground. In this simulated image the extended nature of the source is barely discernible and the brightnesses of the individual components cannot be separately determined. We should note that visual comparison of the images of the extended source taken on March 26 and April 7 reveals small differences. Taken at face value, these differences could be interpreted as indicating changes in either the relative brightness of different parts of the extended source, or in its position. However, no such definitive statement can be made, given the errors involved in the fluxes. This conclusion is further strengthened by the following exercise. We subtracted the image of April 7 from that of March 26, and the result is presented in Fig. 1b. As can be seen, the point source is clearly visible in the subtracted image (which is consistent with its decline in brightness), while no trace of the extended source may be distinguished from the background noise. Thus, within the errors, it appears that the extended source (which dominates the light after March 13) remained constant.

If the extended source was indeed declining (or changing in position), the implication would have been that it is probably powered by the GRB. Since

Table 1: HST Photometry of GRB 970228 Field*

Source	Date (UT)	V	I
Point Source	Mar. 26.4	26.1 ±0.1	24.2 ±0.1
Point Source	Apr. 7.2	26.4 ±0.1	24.6 ±0.1
Ext. Source	Mar. 26.4	24.9 ±0.3	24.5 ±0.3
Ext. Source	Apr. 7.2	25.2 ±0.35	24.3 ±0.35

* The magnitudes given here are in the Cousins bands, where the magnitudes have been transformed from WFPC2 to Cousins filters taking an appropriate colour correction into account. For colour correction, an M2 type spectrum is assumed for the point source and an F2 type spectrum is assumed for the extended source. Since Cousins I filter is similar to F814W, the color correction is close to zero in the I band.

the angular dimensions of the source are about 1 arcsecond, a brightness variation in 15 days would imply a distance to the source of no more than about 2.7 kpc (assuming that the optical light comes from the source location, and is not light scattered from an intervening "screen"). Such a short distance would not be consistent even with models which place GRBs in an extended Galactic halo[31], since these models require typically distances significantly larger than the distance between Earth and the Galactic centre. Models placing all the GRBs in the Galactic disk have been convincingly ruled out by observations[32]. Clearly, with only one optical counterpart to date, we cannot rule out the possibility of the existence of two populations of GRBs[33,34], one at cosmological distances and the other of Galactic origin. The above discussion does suggest that the extended source remained constant and that the apparent decline in brightness is merely a consequence of the low resolution of the ground-based observations. If this interpretation is correct, then the extended source could be an external galaxy (its colour is inconsistent with it being Galactic cirrus as seen in the infrared observations of IRAS). We should also note that the observations of SAX LECS indicate an absorption towards the source of $A_v \simeq 2.5$ magnitudes. With the foreground extinction being[35] $A_v = 0.4 \pm 0.3$, this could indicate absorption in

a galaxy (although the possibility of circumstellar absorption in the vicinity of the source cannot be ruled out).

Since we have found that the optical counterpart may be associated with a galaxy, we first have to determine the probability of a chance superposition. The latter can be estimated by the fractional area covered by galaxies of 25th magnitude (in V), or brighter. From the catalog computed from the Hubble Deep Field (HDF)[36] using the software package FOCAS, we derive a probability for chance superposition of the order of 4%. This is consistent with the probability estimates of van Paradijs et al.[7]

In the following we will therefore assume that the GRB is located in an external galaxy and we will examine the implications of this assumption for theoretical models of GRBs.

One of the key components that can lead to a better understanding of GRBs is the question of their location. The isotropy and inhomogeneity in the distribution of the bursts have led to two leading classes of models, one placing the sources at cosmological distances[32], and the other placing them in the extended Galactic halo[31]. The association of GRB 970228 with an external galaxy would clearly support the cosmological models.

A second question that can be addressed is whether GRBs are associated with nuclear activity of active galactic nuclei (e.g. the burst being produced by tidal disruption of a star[37]). The HST observations clearly show that the optical counterpart is not located at the centre of the brightness distribution, suggesting that GRB 970228 is not at the centre of the host "galaxy." Although inconclusive, this suggests that GRBs as a class are not related to central supermassive black holes.

Irrespective of the nature of the extended source (but assuming that the optical transient point source is indeed the GRB), the data provide valuable information on the evolution of GRB remnants. In particular, specific predictions for the time behaviour of the optical emission from cooling and expanding fireball ejecta (in the context of cosmological models) were made by Meszaros and Rees[13] and (for X-rays in the context of Galactic halo models) by Liang et al.[38]. In Fig. 2, we show the predictions of the impulsive fireball models of Meszaros and Rees and the model by Liang et al., in which cooling of the non-thermal leptons occurs by saturated Compton upscatter-

ing, together with the optical observations. As seen in the figure, our results are consistent with a simple impulsive model[13] in which only the forward blast wave radiates efficiently and in which the peak frequency drops below the optical band about 1.7 days after the burst ($t_{opt} \sim 1.7$ days). It is important to note that the observations rule out models[13] in which the energy input is continuous rather than impulsive, in their simplest form. These models produce either no optical flux at all after the gamma-ray flash, or a flux which declines like t^{-6}, much faster than observed. We should also note that the blast wave models predict a change in their power law (towards a steeper decline) after the blast wave has snowplowed through a rest-mass energy of the order of the burst energy. This predicts a change in the power law after a few days, for a burst energy of 10^{42} ergs (corresponding to extended Galactic halo models). No such change has been observed. If anything, a change in the power law to a shallower decline may have been detected[39] on March 6. This tends to support a cosmological origin for the burst (in which case a change is expected only after a time scale of years).

The fact that cosmological models require peak luminosities of the order of 10^{51} erg s^{-1} has led to the popularity of models involving the mergers of either two neutron stars, or a neutron star and a black hole[40,41]. The frequencies of such mergers have been estimated by Phinney[42] and by Narayan, Piran and Shemi[43]. Using the "best guess" values for the parameters from Phinney and a Hubble constant of $H_0 = 65$ km s^{-1} Mpc^{-1}, we obtain for the ratio of the neutron star merger rate in disk galaxies to that in ellipticals $R_{disk}/R_{elliptical} \simeq 80$. Thus, if GRBs are produced by such mergers, then binaries in disks should dominate the observed rate. A close examination of the "host galaxy" of GRB 970228 (Fig. 1a) reveals indeed elongated features to the east, which are suggestive of a spiral, or irregular morphology, rather than an elliptical one. Furthermore, the $V - I$ colour of the extended source (admittedly uncertain) suggests a late-type galaxy.

A definitive answer to the nature of the extended source associated with GRB 970228 will be provided by HST observations after a longer time interval.

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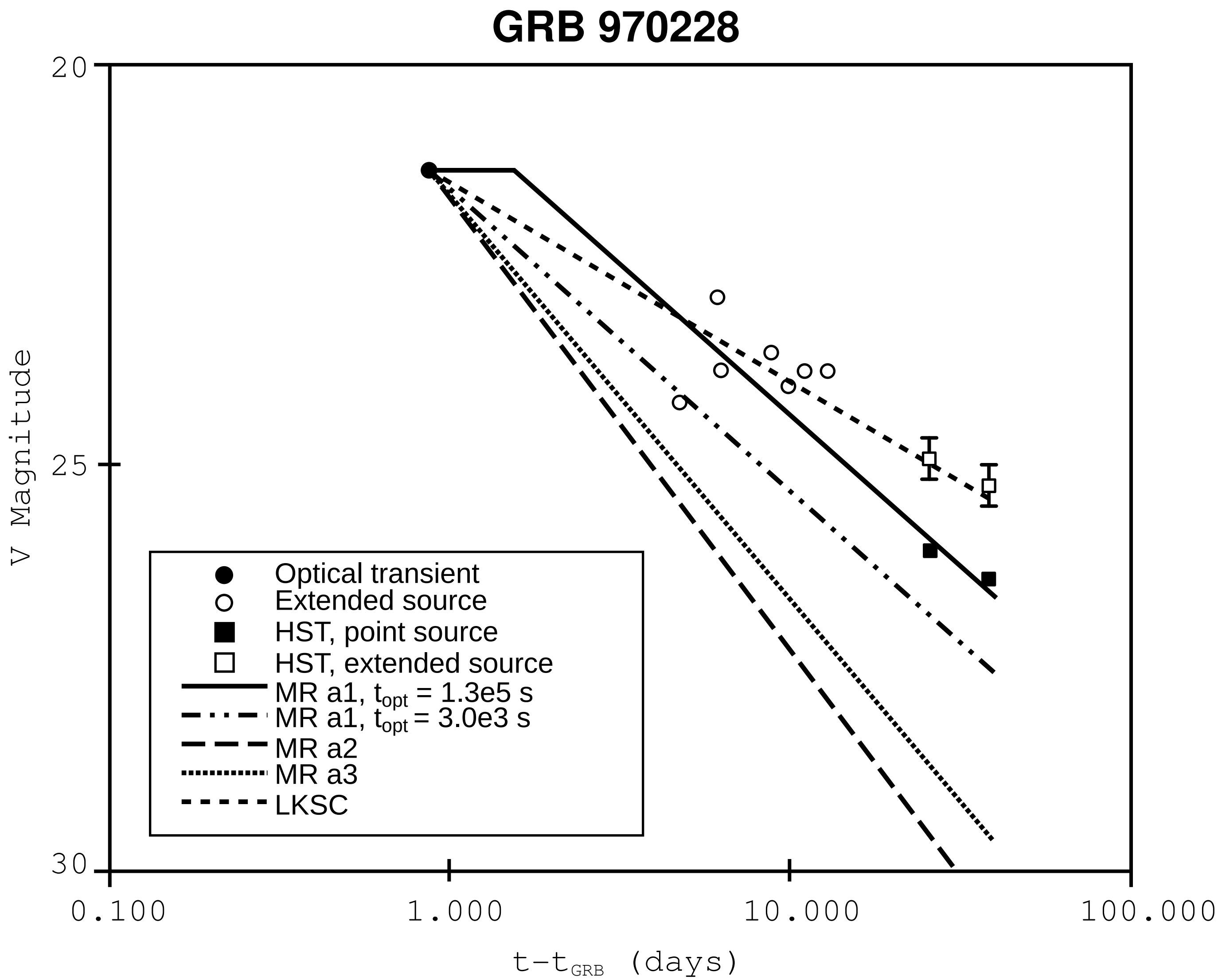
Figure captions

Fig. 1a. The optical counterpart to GRB 970228 was observed with the HST Wide Field and Planetary Camera (WFPC2), between March 26.33 and 26.49 UT, about 26 days after the outburst[14], and again between April 7.15 and 7.32 UT, 39 days after the outburst[15]. Fig a, shows the sum of the F606W and F814W images (resolution 0.045 arcseconds/pixel) taken at both epochs smoothed with a 3x3 spatial filter. The small axes indicate the directions of north (arrow) and east, and the size of the image is 11.5 x 11.5 arcsec. The point source is at the centre of this image, and it is embedded in a diffuse source, 0.3 arcseconds to the north.

Fig. 1b. The difference image obtained by subtracting the summed image of April 7 from the summed image of March 26 (amplified 4 times with respect to **a**. The point source is clearly seen, but there is no trace of the extended source. This is consistent with fading of the point source and constancy of the extended source (within errors) between the two observations.

Fig. 2 Measured brightness of GRB 970228 optical counterpart and models of gamma-ray burster remnants. The brightness of the optical counterpart has been measured by Groot et al. in the 4.2-m William Herschel Telescope discovery image[6,7] (closed circle, labeled Optical Transient). The HST measurements presented in this Letter are indicated by a closed square (point source) and open square (adjacent extended source). The measured brightness[6,7,12,44] of an extended source at the position of the transient is indicated by open circles. The Meszaros and Rees models[13] for the brightness of GRB remnants are labeled MR. In model a1, only the forward blast wave radiates efficiently; in model a2, both the forward and the reverse shocks are efficient radiators; model a3 is similar to a2, but has a different origin for the magnetic field. The Liang et al. model[38] is labeled LKSC. $t - t_{GRB}$ is the time elepsed since the outburst; t_{opt} is the time at which the peak frequency drops below the optical band.



GRB 970228
20
25
30
0.100
1.000
10.000
100.000
V Magnitude
t−t$_{GRB}$ (days)
Optical transient
Extended source
HST, point source
HST, extended source
MR a1, t_{opt} = 1.3e5 s
MR a1, t_{opt} = 3.0e3 s
MR a2
MR a3
LKSC